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The objectives of the program are to educate and train the future workforce through a national student satellite design and fabrication competition and to enable small satellite research and development (R&D), payload development, integration and flight test.

14. ABSTRACT
BUSAT is a comprehensive, integrated nanosatellite project involving graduate students, undergraduate students, and faculty in the engineering and science departments of Boston University and Taylor University. The purpose of the proposed satellite is to perform measurements of the precipitating energetic electron fluxes from low Earth orbit over the high latitude auroral zones and to simultaneously image the auroral emissions caused by these electrons. All milestone activities planned for the project were met.

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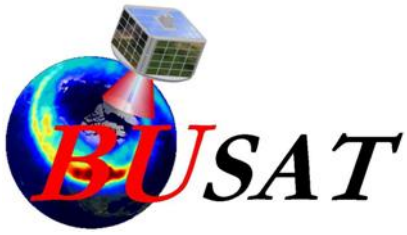


BUSAT (NANOSAT-5) PROGRAM FINAL REPORT

ICN: (Fritz) FA9550-07-1-0204

April 15, 2009

Boston University
Center for Space Physics
Boston, MA 02215

Taylor University
Upland, IN 46989

ABSTRACT

BUSAT is a comprehensive, integrated nano-satellite project involving graduate students, undergraduate students, and faculty in the engineering and science departments of Boston University. The purpose of the proposed satellite is to perform measurements of the precipitating energetic electron fluxes from low Earth orbit over the high latitude auroral zones and to simultaneously image the auroral emissions caused by these electrons. The Boston University Center for Space Physics is a leading space weather research institution and is involved in the study of auroral emissions with ground-based radars, optical instruments, and magnetometers. Present efforts to characterize the electron energy spectrum from the information obtained by these ground based instruments is a main thrust of this research but these efforts are limited by lack of the measured electron precipitating fluxes directly. The proposed satellite will permit this loop to be effectively closed. The satellite structure and bus rely on the cube-sat concept developed by prior nanosat funded efforts at a number of universities and has relied specifically on the experience gained in such a program at Taylor University (Uplands, IN). The communication (command and telemetry) subsystem has been procured via a subcontract directly with TU. Many of the TU designs have been utilized for BUSAT but have been developed and fabricated by student teams at BU. The required auroral imager and imaging electron spectrometer (IES) were fabricated by BU student teams relying on the in-depth experience with such instruments by BU faculty. All subsystems and structural components of BUSAT were brought to a near operational status of the Final Competition Review (FCR) held in Albuquerque, NM in late January. As this was a competition, BUSAT was not selected for flight. The design of BUSAT is unique and innovative and has very real application to the desire to rapidly place or replace sensor systems in orbit.

SCIENCE MISSION

1 SUMMARY

The primary objective of the BUSAT mission is to make a significant contribution to the science of space environment forecasting while concurrently training students in space hardware development and space environment research and applications. The mission goals were as follows:

- **Primary Mission 1:** Design and build a five-instrument satellite (BUSAT) to gather data for testing and developing space-environment applications and related research;
- **Primary Mission 2:** Perform measurements of the precipitating energetic electron fluxes from low Earth orbit over the high latitude auroral zones and to simultaneously image the auroral emissions caused by these electrons in order to better understand the coupling between the Earth's Magnetosphere and Ionosphere
- **Secondary Mission:** Construct a modular satellite subsystem bus design allowing for standardized mechanical and electrical interfaces.

2 OBJECTIVE AND SIGNIFICANT ASPECTS

Over the past fifty years since the advent of the space age with the launch of the first Earth satellites, the space science community has learned much about the geospace environment through space- and ground-based measurements, their ensuing data analysis, and theoretical models. During this time, the

field of space physics has naturally evolved from one that was initially exploratory, to one that is now attempting to synthesize and quantify the inherently dynamic elements that comprise the spatially extended but closely coupled magnetospheric system. One principle characteristic of the magnetospheric system is its dynamism. The magnetospheric fields and particles respond in a coupled fashion to time variations in the solar wind plasma and interplanetary magnetic fields. These externally-induced changes in magnetospheric parameters can be profound: ions and electrons may be substantially energized; boundary layers separating vastly different particle populations may move rapidly; strong electrical currents may flow and dissipate energy in the auroral zone; etc. Much progress over the past five decades of space physics research has allowed us to attempt to develop ever improving quantitative and predictive models of this dynamic system but a great deal of the underlying physics remains undetermined and/or understood.

3 IMPLEMENTATION

The prime BUSAT objectives center on using students to build satellite hardware to enable them to obtain data to predict the incident energy spectrum of the precipitating electrons responsible for producing the auroral emissions being measured. In order to achieve the scientific objectives outlined above the following complement of scientific instruments have been fabricated and are included as part of the BUSAT payload.

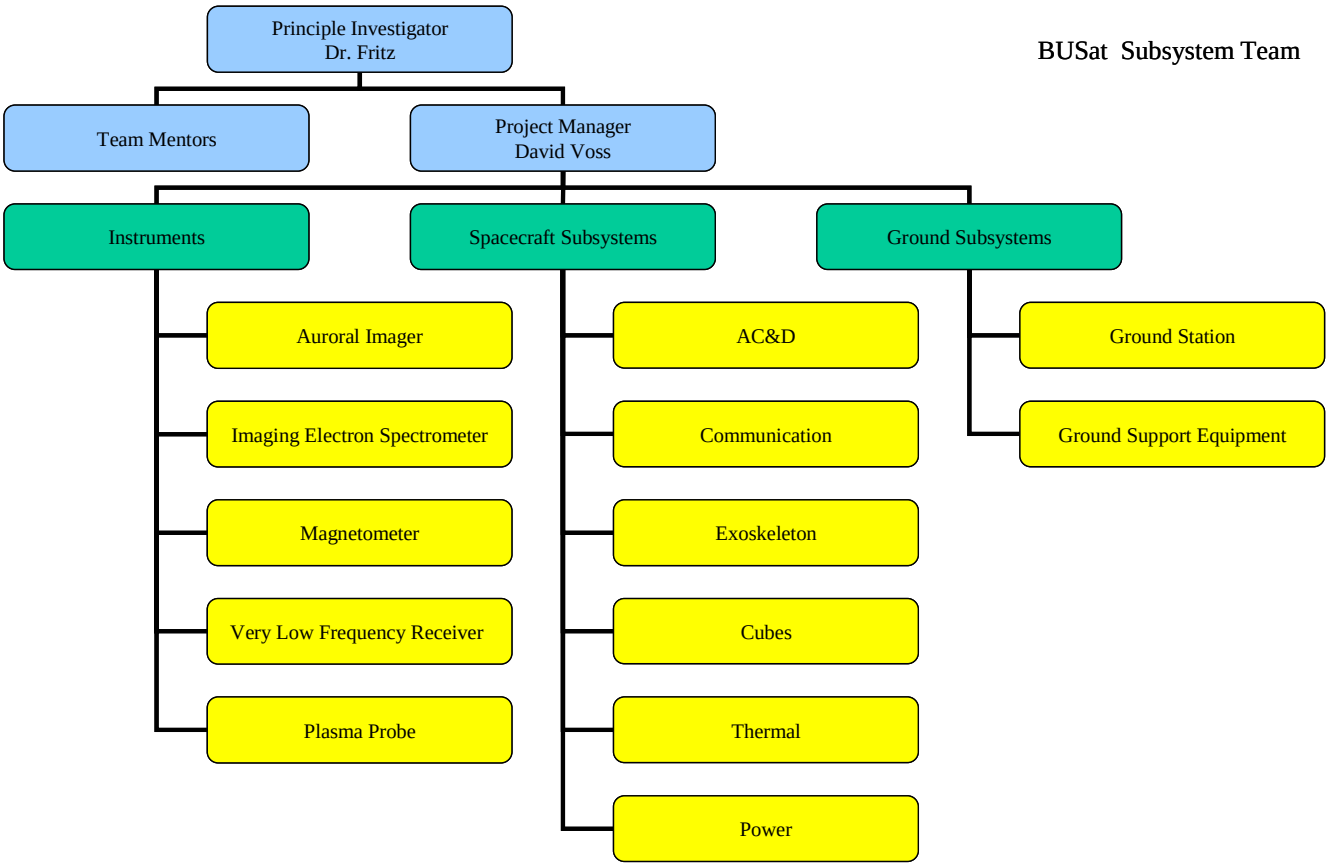
Table 1 - Summary of instruments on BUSAT and their measurement sensitivity

Instrument	Measurement	Range
1. Magnetometer	Magnetic Field	>10nT
2. Auroral Imager	Auroral Emissions	390nm to 650nm
3. IES	Energetic Electrons	30 keV to 500 keV
4. Langmuir Plasma Probe	Electron and Ion Density	Thermal 0 to 6 eV
5. Very Low Frequency Receiver	EM waves	100Hz – 30 kHz

MANAGEMENT

1 ORGANIZATIONAL

The BUSAT instrument development team has been made up of 13 teams involving students from four departments and three colleges at Boston University. We have attempted to implant a management structure that relies on the mentorship of experienced individuals, while allowing undergraduates to take a leading role in the design and development of the BUSAT. The mentoring of the students comes from a variety of people including professors, graduate students, and research associates. The management structure can be seen in the figure below.



2 STUDENT INVOLVEMENT

There has been a large undergraduate involvement in the design and construction of BUSAT. We have had over 70 students work on the project since the initial funding of the project, with more than 30 of the students taking a very active role in the development of the project. The figure below shows the involvement of students and their skill sets, versus the needs to design and complete BUSAT. As can be seen from the chart the involvement of students from the departments of Aerospace Engineering, Mechanical Engineering, Electrical and Computer Engineering, Department of Astronomy, and the School of Management, has provided a diverse set of skills. Students have almost exclusively come from the college of engineering, though we have had some involvement from students in the Department of Astronomy and the School of Management. With the financial help of a number of offices and centers at Boston University (the Provost, the Dean of Engineering, the Associate Dean of Arts and Sciences, the Director of the Photonics Center, the Director of the Center for Space Physics, the Chair of the Department of Electrical and Computer Engineering, the Chair of the Department of Aerospace and Mechanical Engineering) and individual faculty and staff, it was possible to employ approximately 30 student full time for ten weeks during each of the summers of 2007 and 2008. There students were given flexible hours and required to work 40 hours per week. A “brown bag” lunchtime presentation with required attendance was made twice per week to describe progress in the design and development of the BUSAT designs and hardware. The picture below shows the 2008 summer team.

	PI	Co-PI	Administrative Support	Project Manager	Graduate Students	Team Spokesperson	AE	ME	EE	CSE	AS	ES
Science Requirements	X	X		X	X						X	X
Structural Requirements	X	X		X			X	X				
Electrical Requirements	X	X		X	X				X	X		
System Requirements	X	X		X		X						
Circuit Design/PCB Fabrication									X	X		
Structure Fabrication							X	X				
Thermal Analysis							X	X				
FEA Analysis							X	X				
Orbital Analysis							X	X				
Documentation			X	X	X	X	X	X	X	X	X	X
Schedule	X			X		X						
Budget	X		X	X		X						
Parts Selection and Procurement	X		X	X		X						

3 ACADEMIC CREDIT

The BUSAT student teams have been able to take advantage of the work they have been doing on BUSAT and apply it for academic credit. The willingness of the various departments to grant both independent study as well as senior design projects as qualifying projects for academic requirements has demonstrated the support that BUSAT has with the Boston University administration. We have had a senior design team of four students who developed the C&DH subsystem as part of their senior design project for the ECE department and one senior design team who has developed the Plasma Probe Instrument and the VLF Instrument for their senior design project. There have also been ten students who have done independent studies on various subsystems for academic credit supervised by four different faculty members. At least 62 hours of academic credit have been earned to date by BUSAT students on project related activities during the four semesters of the project.

Student/s	Type of Credit	Area
4 students	Senior Design Project	Command and Data Handling Subsystem
3 students	Senior Design Project	VLF and Plasma Probe Instruments
4 students	Independent Studies	Attitude Control
4 students	Independent Studies	IES Instrument

4 PARTNERSHIPS

The BUSAT team is composed of a variety of partnerships. The first major partnership is between Taylor University and Boston University, where Taylor has acted as a subcontractor and delivered two instruments and the communication subsystem. At Boston University, BUSAT has brought together three colleges and several research centers noted in Section 2. In addition the BUSAT team has benefited from the following companies: Alstom Aerospace who provided BUSAT with a comprehensive thermal analysis package known as the ESATAN Thermal Analyzer; C&R Technologies who provided the following software for the thermal team: SINDA/FLUINT, a generalized thermal/fluid network-style solver and Thermal Desktop, a PC/CAD-based thermal model builder; and Scadata who provided BUSAT with support and modifications for the freewave radios.

5 BUDGET

BUSAT has been on-budget for the fabrication costs that were estimated in the proposal. Significant financial assistance from the Boston University administration has allowed the BUSAT management to employ a large number of students for both the summers of 2007 and 2008. As noted above this permitted approximately 30 undergraduate students to work on the BUSAT project full-time for a ten-week period during each summer. The budget estimates and actual expenses can be seen in the below table.

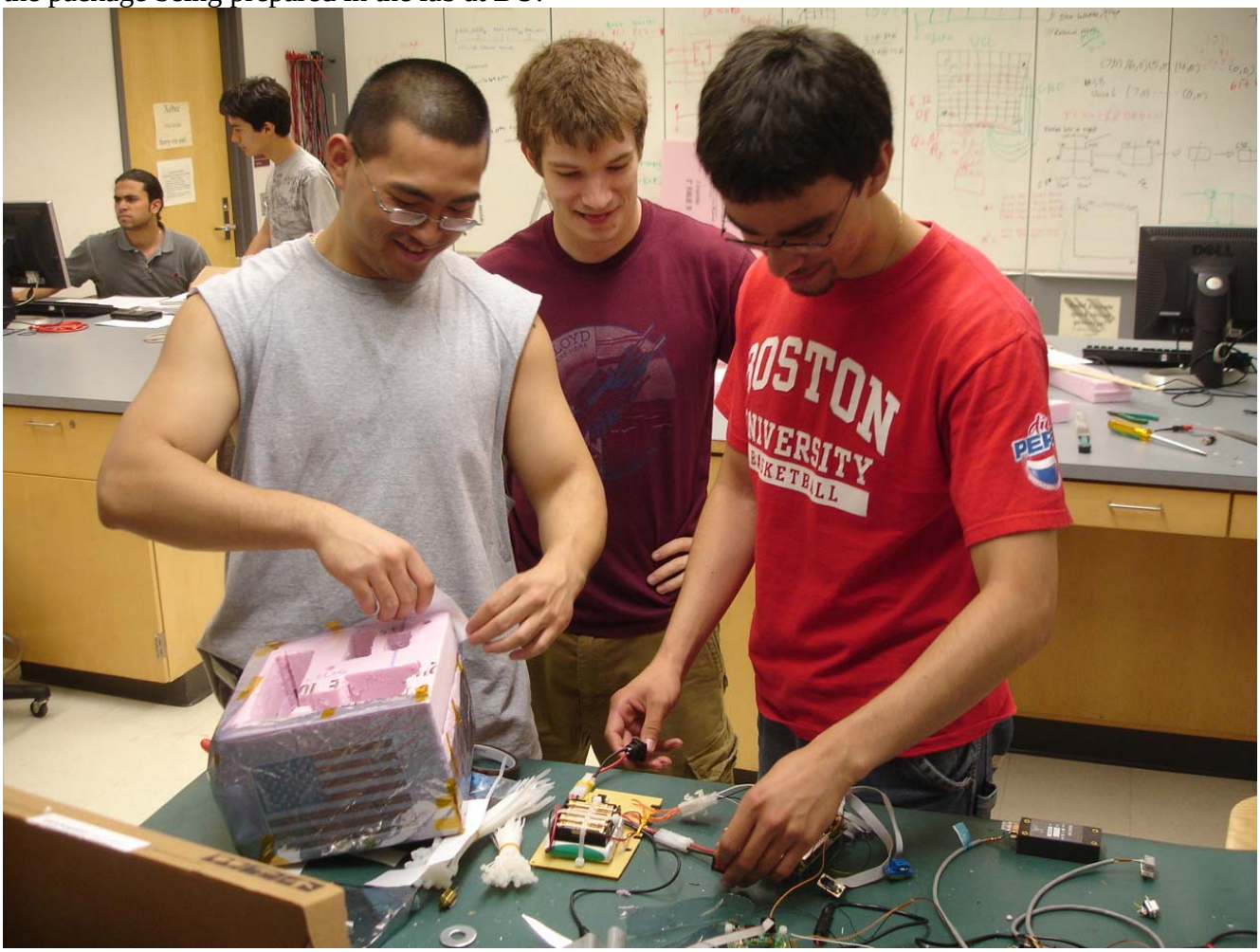
Area	Proposed Budget	Actual Expenses	BU investment
Fabrication	$25,000	$26,000	
Student salaries	$40,000	$225,000	185000
Taylor subcontract	$15,000	$15,000	
Project Supplies	$1,000	$1,800	
Travel	$2,100	$5,400	5000
Other costs	$26,900	$26,800	
Total	110000	300000	190000
less BU contribution		110000	

6 SHOT 1 WORKSHOP

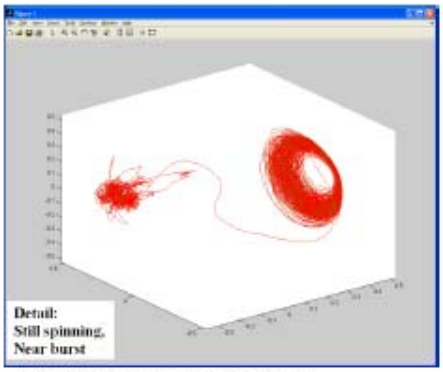
Students from the BUSAT project were able to take part in the Air Force organized SHOT 1 workshop that was held in Colorado during the summer of 2007. During this workshop four of our undergraduate team leaders and one of our team mentors were able to take part in activities that helped build good design practices. Below is a picture of those students resulting in the package flown on a high altitude balloon arising from that experience.

7 SHOT 2 WORKSHOP

The SHOT-2 workshop was also held in Boulder, CO and the three of the BUSAT team prepared the preliminary version of the satellite magnetometer for a balloon flight test. The picture below shows the package being prepared in the lab at BU.



The package was flown and was the only instrument to function fully and return data from the balloon flight. To the right is a plot of the three axis data measured by magnetometer during the balloon flight at the SHOT 2 workshop.



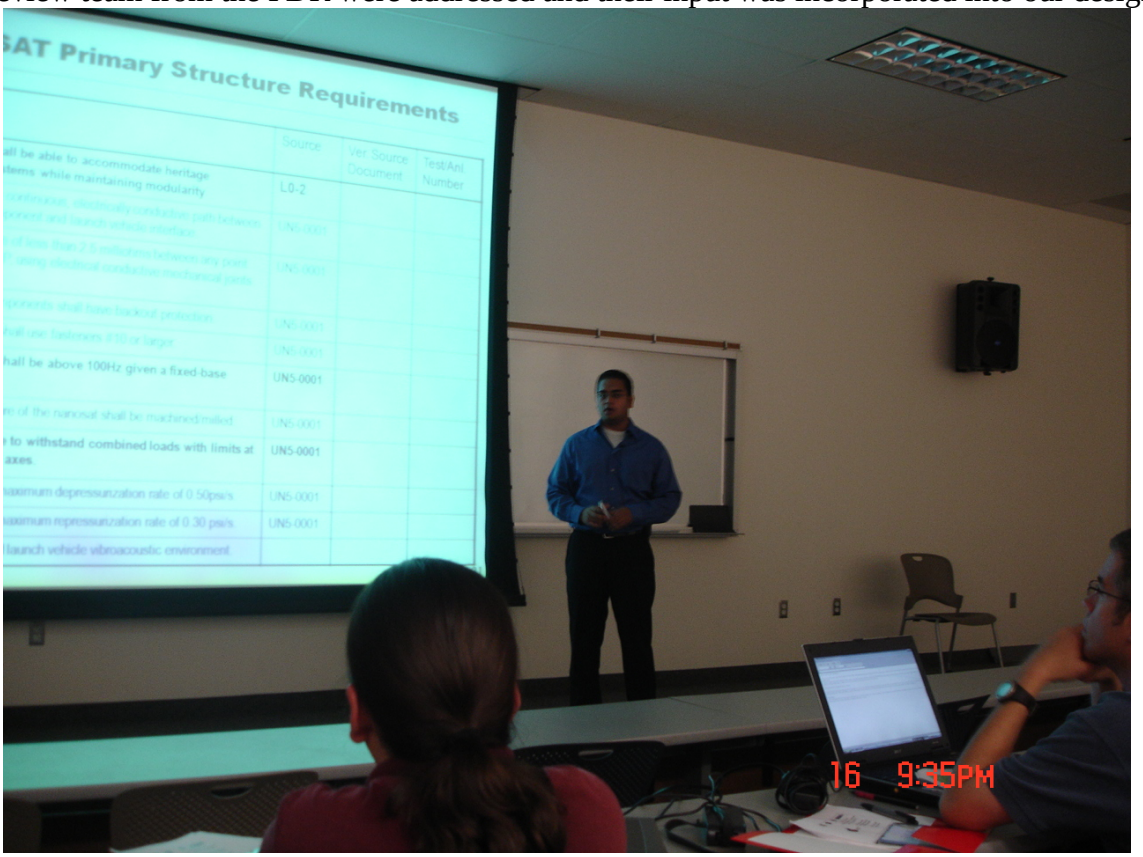
Matlab plot of data from magnetometer on SHOT II balloon launch

TECHNICAL

1 REVIEWS

The BUSAT team has gone through all of the required reviews. The first review was the System Concept Review that was held via telecom in April of 2007. At this review the BUSAT team submitted slides on the management structure, the mission requirements, and an overview of the system design.

The second review was the Preliminary Design Review (PDR) that was held in Logan Utah and followed the Utah State Small Satellite Conference. We had three presenters that had to cover the entire spacecraft design, management philosophy, and requirements in 45 minutes. The image below is one of our Team Leaders presenting at the PDR. A number of action items that were created by the Air Force review team from the PDR were addressed and their input was incorporated into our design.



The final design review we have had was our Critical Design Review that was held in April 2008. At this review six reviewers from the Air Force traveled to Boston University where we held an all day review on the BUSAT project. This was an extensive review on the management, requirements, design, and current progress on BUSAT. We had over 15 presenters, essentially all being undergraduate students and/or graduate students. Taylor University was able to participate in the program as well presenting on their two instruments and the communication subsystem.

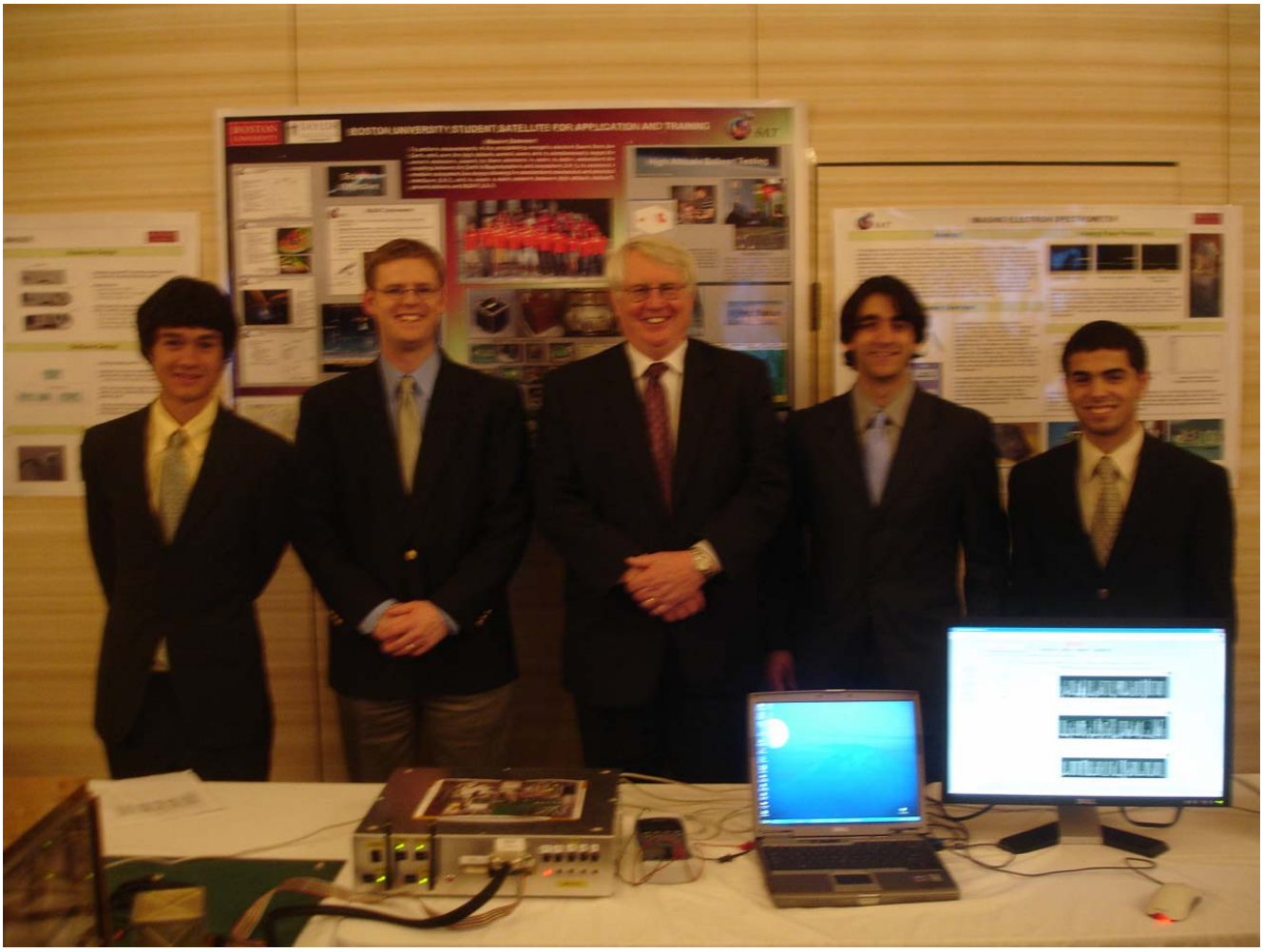
The Preliminary Qualification Review was held during the Small Satellite Conference in Logan, Utah in August of 2008. Four team members plus the PI participated in the review which consisted of a

booth that team members would take turns being present to answer questions from the US Air Force review team. The picture below is of the BUSAT team members in front of the BUSAT booth

The table below summarizes the BUSAT team support of the required project reviews including the PI.

Milestone	Date	Location	Attendance
Kickoff Meeting	Jan-07	Telecon	Yes, 2
Expert Area Telecons	Jan-Dec 2007	Telecons	Yes (all telecons, 5 to 15 students in attendance at each)
SCR	April/May 2007	Telecon	Yes- 15
SHOT I	June 12-15, 2007	Boulder, CO	Yes – 5
PDR	August 16-17, 2007	Logan, UT	Yes – 5
Sat-Fab Class	Nov-07	Albuquerque , NM	Yes – 4
CDR	Feb-April 2008	Boston, MA	Yes - ~20
SHOT II	June 13-15, 2008	Boulder CO	Yes – 4
PQR	August 11-14, 2008	Logan, UT	Yes – 5
FCR	20-Jan-09	Albuquerque, NM	Yes – 4

The final competition review was held in Albuquerque, NM in January 2009. The BUSAT team returned from their Christmas break and put in many long hours and near sleepless nights to get the satellite to a functional status. This was described in a *BU Synapse* article by Ryan et al. (2009). A team of four students plus the PI presented the BUSAT project and payload to the Air Force Review team at the FCR and is pictured below. The competition was won by a team from the University of Colorado.



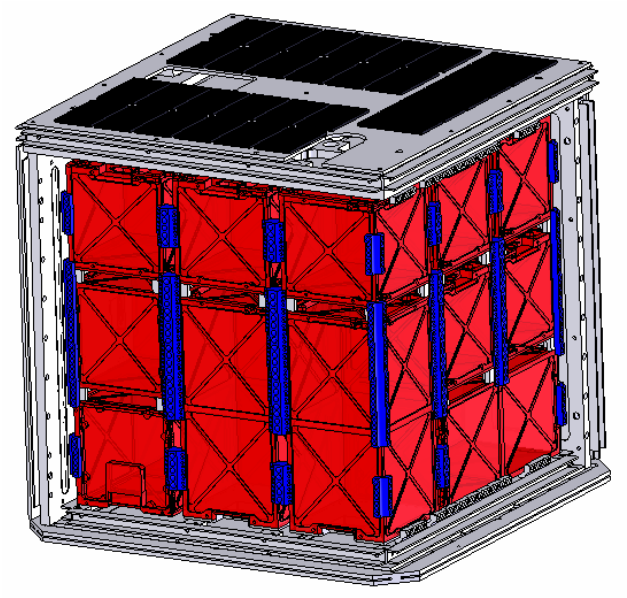
2 STATUS

2.1 Mechanical

In the two years of the BUSAT project, it moved from a conceptual design, to an analyzed and documented design, to a fabricated structure and mostly functional set of electronics for the experiment instrument. A drawing of the proposed design can be seen to the left in the figure below with two of the side walls hidden and an image of the fully fabricated satellite structure can be seen to the right.

Students were intimately involved in every step of the design and analysis of the BUSAT mechanical design. Current fabrication of the structure is complete and the design could be verified through a vibration qualification test if additional funding were available. The five instruments and satellite

subsystems were about 85% complete at FCR. The satellite structure is unique in permitting a rapid integration of any instrument that could be placed in a four inch cube. This structural design could be of great interest to the spaceflight community interested in "operationally responsiveness to space" (ORS) and this has been described in a paper by Voss et al. (2009).



The BUSAT as proposed

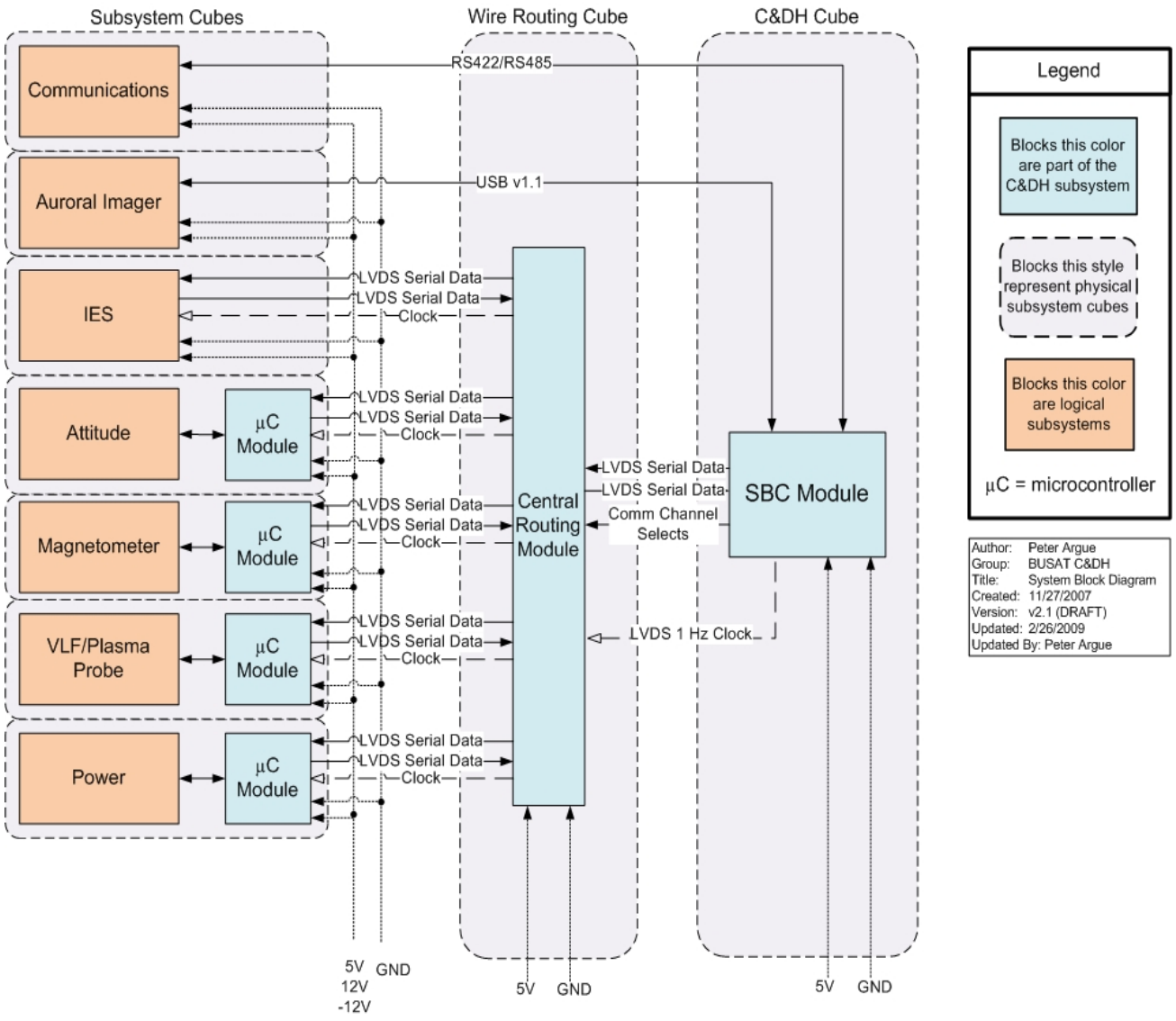
The BUSAT as designed and fabricated

2.2 Electrical

The BUSAT electrical design is designed around a single board computer (SBC) that pulls the various subsystems in a simple polling scheme. The SBC is a VIPER 386 computer running a version of Linux. The SBC collects data from each instrument or subsystem one at a time, stores the data, and transmits it to the ground when over Boston University. The logic block diagram for BUSAT can be seen in the below figure.

CONCLUSION

The BUSAT team met the goals of the project for a delivery of a flight version of a functional satellite in January of 2009. The project has provided a platform for students to apply the theories they have learned in classes to real world problems. It has involved a large number of students in multiple universities, centers, and departments. It is a spacecraft that has a real application to assist the Air Force in a very pertinent area of current research with better understanding the coupling of particles in the magnetosphere to the ionosphere. The Principal Investigator hopes to find a way to bring the BUSAT to flight status and obtain a launch for the satellite.



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David Voss, Joseph Coombs, Theodore Fritz, and Jeff Dailey, "A novel spacecraft standard for a modular nanosatellite bus in an operationally responsive space environment", presented at the AIAA/7th Responsive Space® Conference 2009